Measurement of the $t\bar{t}$ production cross section in the all-jets final state in pp collisions at $\sqrt{s} = 8$ TeV

CMS Collaboration ; Canelli, F ; Chiochia, V ; Kilminster, B ; Robmann, P ; et al

Abstract: The cross section for $t\bar{t}$ production in the all-jets final state is measured in pp collisions at a centre-of-mass energy of 8 TeV at the LHC with the CMS detector, in data corre- sponding to an integrated luminosity of 18.4 fb^1. The inclusive cross section is found to be 275.6 ± 6.1 (stat) ± 37.8 (syst) ± 7.2 (lumi) pb. The normalized differential cross sections are measured as a function of the top quark transverse momenta, pT, and compared to predictions from quantum chromodynamics. The results are reported at detector, parton, and particle levels. In all cases, the measured top quark pT spectra are significantly softer than theoretical predictions.

DOI: https://doi.org/10.1140/epjc/s10052-016-3956-5

Originally published at:
CMS Collaboration; Canelli, F; Chiochia, V; Kilminster, B; Robmann, P; et al (2016). Measurement of the $t\bar{t}$ production cross section in the all-jets final state in pp collisions at $\sqrt{s} = 8$ TeV. European Physical Journal C - Particles and Fields, 76(3):128.
DOI: https://doi.org/10.1140/epjc/s10052-016-3956-5

CERN-PH-EP/2013-037
2016/03/15

CMS-TOP-14-018

Measurement of the $\mathrm{t\bar{t}}$ production cross section in the all-jets final state in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The cross section for $\mathrm{t\bar{t}}$ production in the all-jets final state is measured in pp collisions at a centre-of-mass energy of 8 TeV at the LHC with the CMS detector, in data corresponding to an integrated luminosity of $18.4\,\mathrm{fb}^{-1}$. The inclusive cross section is found to be $275.6 \pm 6.1\,\mathrm{(stat)} \pm 37.8\,\mathrm{(syst)} \pm 7.2\,\mathrm{(lumi)}\,\mathrm{pb}$. The normalized differential cross sections are measured as a function of the top quark transverse momenta, p_{T}, and compared to predictions from quantum chromodynamics. The results are reported at detector, parton, and particle levels. In all cases, the measured top quark p_{T} spectra are significantly softer than theoretical predictions.

Published in the European Physical Journal C as doi:10.1140/epjc/s10052-016-3956-5.

*See Appendix A for the list of collaboration members

1 Introduction

The top quark is an important component of the standard model (SM), especially because of its large mass, and its properties are critical for the overall understanding of the theory. Measurements of the top quark-antiquark pair ($t\bar{t}$) production cross section test the predictions of quantum chromodynamics (QCD), constrain QCD parameters, and are sensitive to physics beyond the SM. The $t\bar{t}$ process is also the dominant SM background to many searches for new physical phenomena, and its precise measurement is essential for claiming new discoveries.

The copious top quark data samples produced at the CERN LHC enable measurements of the $t\bar{t}$ production rate in extended parts of the phase space, and differentially as a function of the kinematic properties of the $t\bar{t}$ system. Inclusive and differential cross section measurements from proton-proton (pp) collisions at centre-of-mass energies of 7 and 8 TeV have been reported by the ATLAS [1–11] and CMS collaborations [12–24]. These are significantly more precise than the measurements of $t\bar{t}$ production in proton-antiproton collisions performed at the Tevatron [25]. In this paper, we report new results from pp collision data at $\sqrt{s} = 8\,\text{TeV}$, collected with the CMS detector. Measurements of the $t\bar{t}$ inclusive cross section and the normalized differential cross sections are presented for the first time in the all-jets final state at this collision energy. The results are compared to QCD predictions, and are in agreement with other measurements in different decay channels.

Top quarks decay almost exclusively into a W boson and a b quark. Events in which both W bosons from the $t\bar{t}$ decay produce a pair of light quarks constitute the so-called all-jets channel. As a result, the final state consists of at least six partons (more are possible from initial- and final-state radiation), two of which are b quarks. Despite the large number of combinatorial possibilities, it is possible to fully reconstruct the kinematical properties of the $t\bar{t}$ decay products, unlike in the leptonic channels where the presence of one or two neutrinos makes the full event interpretation ambiguous. However, the presence of a large background from multijet production, and the larger number of jets in the final state make the measurement of the $t\bar{t}$ cross section in the all-jets final state more uncertain compared to the leptonic channels. Nevertheless, a high-purity signal sample can be selected, which increases significantly the signal-over-background ratio compared to previous measurements in this decay channel [21, 26, 27].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Extensive forward calorimetry (pseudorapidity $|\eta| > 3.0$) complements the coverage provided by the barrel ($|\eta| < 1.3$) and endcap ($1.3 < |\eta| < 3.0$) detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than $4\,\mu$s. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to around 300 Hz, before data storage. A detailed description of the CMS apparatus, together with the definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [28].

3 Event simulation

The $t\bar{t}$ events are simulated using the leading-order (LO) MADGRAPH (v. 5.1.5.11) event generator [29], which incorporates spin correlations through the MADSPIN [30] package and the simulation of up to three additional partons. The value of the top quark mass is set to $m_t = 172.5\,\mathrm{GeV}$ and the proton structure is described by the parton distribution functions (PDFs) from CTEQ6L1 [31]. The generated events are subsequently processed with PYTHIA (v. 6.426) [32] which utilizes tune Z2* for parton showering and hadronization, and the MLM prescription [33] is used for matching of matrix element jets to those from parton shower. The PYTHIA Z2* tune is derived from the Z1* tune [34], which uses the CTEQ5L PDF [31], whereas Z2* adopts CTEQ6L [31]. The CMS detector response is simulated using GEANT4 (v. 9.4) [35].

In addition to the MADGRAPH simulation, predictions obtained with the next-to-leading-order (NLO) generators MC@NLO (v. 3.41) [36] and POWHEG (v. 1.0 r1380) [37] are also compared to the measurements. While POWHEG and MC@NLO are formally equivalent up to NLO accuracy, they differ in the techniques used to avoid double counting of the radiative corrections when interfacing with the parton shower generators. Two different POWHEG samples are used: one uses PYTHIA and the other HERWIG (v. 6.520) [38] for parton showering and hadronization. The events generated with MC@NLO are interfaced with HERWIG. The HERWIG AUET2 tune [39] is used to model the underlying event in the POWHEG+HERWIG sample, while the default tune is used in the MC@NLO+HERWIG sample. The proton structure is described by the PDF sets CT10 [40] and CTEQ6M [31] for POWHEG and MC@NLO, respectively. The QCD multijet events are simulated using MADGRAPH (v. 5.1.3.2) interfaced with PYTHIA (v. 6.424).

4 Event reconstruction and selection

4.1 Jet reconstruction

Jets are reconstructed with the anti-k_T clustering algorithm [41, 42] with a distance parameter of 0.5. The input to the jet clustering algorithm is the collection of particle candidates that are reconstructed with the particle-flow (PF) algorithm [43, 44]. In the PF event reconstruction all stable particles in the event, i.e. electrons, muons, photons, and charged and neutral hadrons, are reconstructed as PF candidates using a combination of all of the subdetector information to obtain an optimal determination of their directions, energies, and types. All the reconstructed vertices in the event are ordered according to the sum of squared transverse momenta (p_T) of tracks used to reconstruct it and the vertex with the largest sum is considered the primary one, while all the rest are considered as pileup vertices. In order to mitigate the effect of multiple interactions in the same bunch crossing (pileup), charged PF candidates that are unambiguously associated with pileup vertices are removed prior to the jet clustering. This procedure is called charged-hadron subtraction (CHS) [45]. An offset correction is applied for the additional energy inside of the jet due to neutral hadrons or photons from pileup. The resulting jets require a small residual energy correction, mostly due to the thresholds for reconstructed tracks and clusters in the PF algorithm and reconstruction inefficiencies [45].

The identification of jets that likely originate from the hadronization of b quarks is done with the “combined secondary vertex” (CSV) b tagger [46]. The CSV algorithm combines the information from track impact parameters and identified secondary vertices within a given jet, and provides a continuous discriminator output.

4.2 Trigger

The data used for this measurement were collected with a multijet trigger event selection (path) which, from the HLT, required at least four jets reconstructed from calorimetric information with a p_{T} threshold of 50 GeV and $|\eta| < 3.0$. The hardware trigger required the presence of two central ($|\eta| < 3.0$) jets above various p_{T} thresholds (52–64 GeV), or the presence of four central jets with lower p_{T} thresholds (32–40 GeV), or the scalar sum of all jets p_{T} to be greater than 125 or 175 GeV. The various thresholds were adjusted within the quoted ranges according to the instantaneous luminosity. The trigger paths employed were unprescaled for a larger part of the run, yielding a data sample corresponding to an integrated luminosity of 18.4 fb^{-1}.

4.3 Selection and kinematic top quark pair reconstruction

Selected events are required to contain at least six reconstructed jets with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.4$ (jets are required to be within the tracker acceptance in order to apply the CHS), with at least four of the jets having $p_{\mathrm{T}} > 60$ GeV (so that the trigger efficiency is greater than 80% and the data-to-simulation correction factor smaller than 10%). Among the six jets with the highest p_{T} (leading jets), at least two must be identified as coming from b hadronization by the CSV algorithm at the medium working point (CSVM), with a typical b quark identification efficiency of 70% and misidentification probability for light quarks of 1.4%, and these are considered the most probable b jet candidates. If there are more than two such jets, which happens in approximately 2% of the events, then the two with the highest p_{T} are chosen. To select events compatible with the $\mathrm{t\bar{t}}$ hypothesis, and to improve the resolution of the reconstructed quantities, a kinematic fit is performed that utilizes the constraints of the $\mathrm{t\bar{t}}$ decay. A χ^2 fit is performed, starting with the reconstructed jet four-momenta, which are varied within their experimental p_{T} and angular resolutions, imposing a W boson mass constraint (80.4 GeV [47]) on the light-quark pairs, and requiring that the top quark and antiquark have equal mass. Out of all the possible combinations from the six input jets, the algorithm returns the one with the smallest χ^2 and the resulting parton four momenta, which are used to compute the reconstructed top quark mass ($m_{\mathrm{t}}^{\mathrm{rec}}$). The probability of the converged kinematic fit is required to be greater than 0.15. Overall, the kinematic fit requirements select approximately 5% (2%) of the $\mathrm{t\bar{t}}$ (background) events. The distance in the η–ϕ space between the two b quark candidates must be $\Delta R_{\mathrm{bb}} = \sqrt{(\Delta\eta_{\mathrm{bb}})^2 + (\Delta\phi_{\mathrm{bb}})^2} > 2.0$, which has an efficiency of roughly 75% (50%) on $\mathrm{t\bar{t}}$ (background) events. The last two requirements are applied to select events with unambiguous top quark pair interpretation and to suppress the QCD background that originates from gluon splitting into collinear b quarks [48].

5 Signal extraction

The background to the $\mathrm{t\bar{t}}$ signal is dominated by the QCD multijet production process, while the other backgrounds, such as the associated production of vector bosons with jets, are negligible. Due to the limited size of the Monte Carlo (MC) simulated samples, the background is determined directly from the data. A QCD-dominated event sample is selected with the trigger and offline requirements described in Section 4.3 and requiring zero CSVM b tagged jets. In these events the most probable b quark candidates are determined by the kinematic fit. The resulting sample contains a negligible fraction of $\mathrm{t\bar{t}}$ events ($< 1\%$) and is treated exactly like the signal sample. After applying the $\Delta R_{\mathrm{bb}} > 2.0$ and the fit probability requirements, the reconstructed top-like kinematic properties of events with no b jet are very similar to those with two b jets (confirmed using simulated QCD events). We use this QCD-dominated control sample to extract the shape (templates) of the various kinematic observables. The number of $\mathrm{t\bar{t}}$ events (signal yield) is extracted from a template fit of m_t^{rec} to the data using parametrized shapes for signal and background distributions, where the signal shape is taken from the $t\bar{t}$ simulation and the QCD shape is taken from the control data sample described above. The background and signal yields are determined via a maximum likelihood fit to the m_t^{rec} distribution and are used to normalize the corresponding samples. Figures 1 and 2 show the fitted mass and the kinematic fit probability and ΔR_{bb} distributions. The p_T distribution of the six leading jets is shown in Fig. 3. From the output of the kinematic fit one can reconstruct the two top quark candidates, whose p_T are shown in Fig. 4, and the properties of the $t\bar{t}$ system (p_T, rapidity y) are shown in Fig. 5. Overall, the data sample is dominated by signal events, and the data are in agreement with the fit results. The jet p_T spectra in data appear to be systematically softer than in the simulation, in agreement with the observations in Ref. [24], related to a softer measured top quark p_T spectrum.

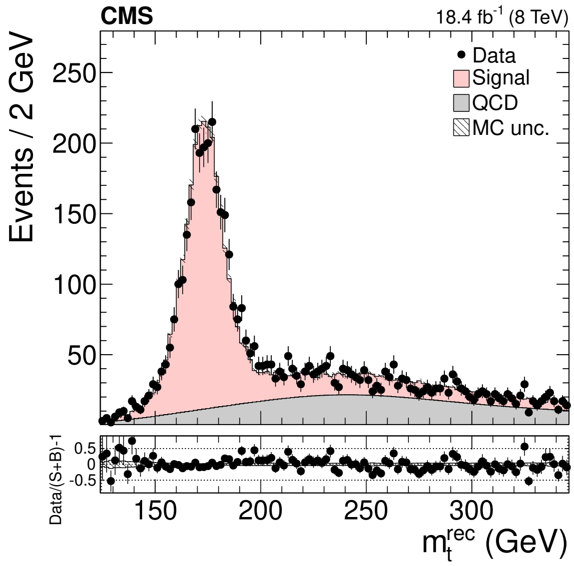

Figure 1: Distribution of the reconstructed top quark mass after the kinematic fit. The normalizations of the $t\bar{t}$ signal and the QCD multijet background are taken from the template fit to the data. The bottom panel shows the fractional difference between the data and the sum of signal and background predictions, with the shaded band representing the MC statistical uncertainty.

6 Systematic uncertainties

The measurement of the $t\bar{t}$ cross section is affected by several sources of systematic uncertainty, both experimental and theoretical, which are described below and summarized in Table 1. The quoted values refer to the inclusive measurement, with small variations observed in the bins of the differential measurement presented in Section 7.2.

- **Background modeling:** the QCD m_t^{rec} template shape derived from the data control sample is varied according to the uncertainty of the method evaluated with simulated events, which impacts the extracted signal yield moderately (4.9%).
- **Trigger efficiency:** the efficiency of the trigger path is taken from the simulation and corrected with an event-by-event scale factor (SF_{trig}), calculated from data independent samples, that depends on the fourth jet p_T. In the phase space of the measurement, the SF_{trig} is greater than 0.83 and on average 0.96. The associated uncertainty is conservatively defined as $(1 - SF_{trig})/2$ and has a small impact (2.0%) on the cross section.

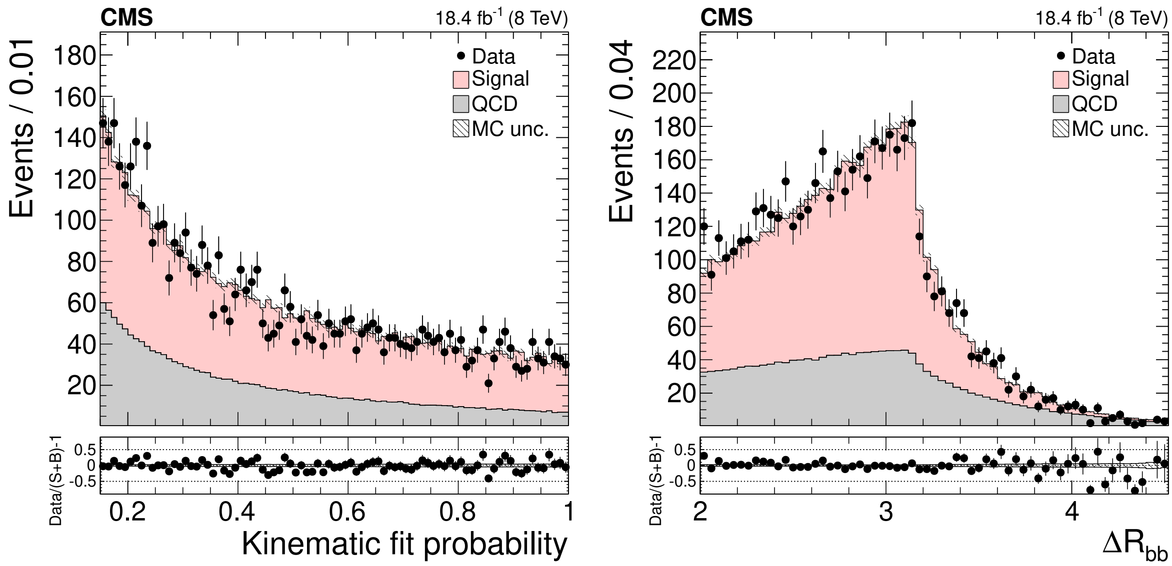

Figure 2: Distribution of the kinematic fit probability (left). Distribution of the distance between the reconstructed b partons in the η–ϕ plane (right). The normalizations of the $t\bar{t}$ signal and the QCD multijet background are taken from the template fit to the data. The bottom panels show the fractional difference between the data and the sum of signal and background predictions, with the shaded band representing the MC statistical uncertainty.

- **Jet energy scale and resolution:** the jet energy scale (JES) and jet resolution (JER) uncertainties have significant impacts on the measured cross section due to the relatively high p_T requirements on the fourth and sixth of the leading jets. In the simulated events, jets are shifted (smeared) according to the p_T- and η-dependent JES (JER) uncertainty, prior to the kinematic fit, and the full event interpretation is repeated. The JES (JER) has a dominant (small) effect on the cross section measurement of 7.0% (3.5%). In addition, the JES/JER uncertainties affect the signal template, with a negligible impact ($\approx$1%) on the cross section measurement.
- **b tagging:** the performance of the b tagger has a dominant effect on the signal acceptance because the selected events are required to have at least two jets satisfying the CSVM requirement. An event-by-event scale factor (SF_{btag}) is applied to the simulation, which accounts for the discrepancies between data and simulation in the efficiency of tagging true b jets and in the misidentification rate [46]. The average value of SF_{btag} is 0.99. The uncertainty in the SF_{btag} is taken into account by weighting each event with the shifted value of SF_{btag} which results in a cross section uncertainty of 7.3%. This is the leading systematic uncertainty.
- **Integrated luminosity:** the uncertainty on the integrated luminosity is estimated to be 2.6% [49].
- **Matching partons to showers:** the impact of the choice of the scale that separates the description of jet production via matrix elements or parton shower in MADGRAPH is studied by changing its reference value of 20 to 40 and 10 GeV, resulting in an asymmetric effect of −4.2, +2.4% on the cross section.
- **Renormalization and factorization scales:** the uncertainty in modelling of the hard-production process is assessed through changes in the renormalization and factorization scales in the MADGRAPH sample by factors of two and half, relative to their common nominal value, which is set to the Q of the hard process. In MAD-

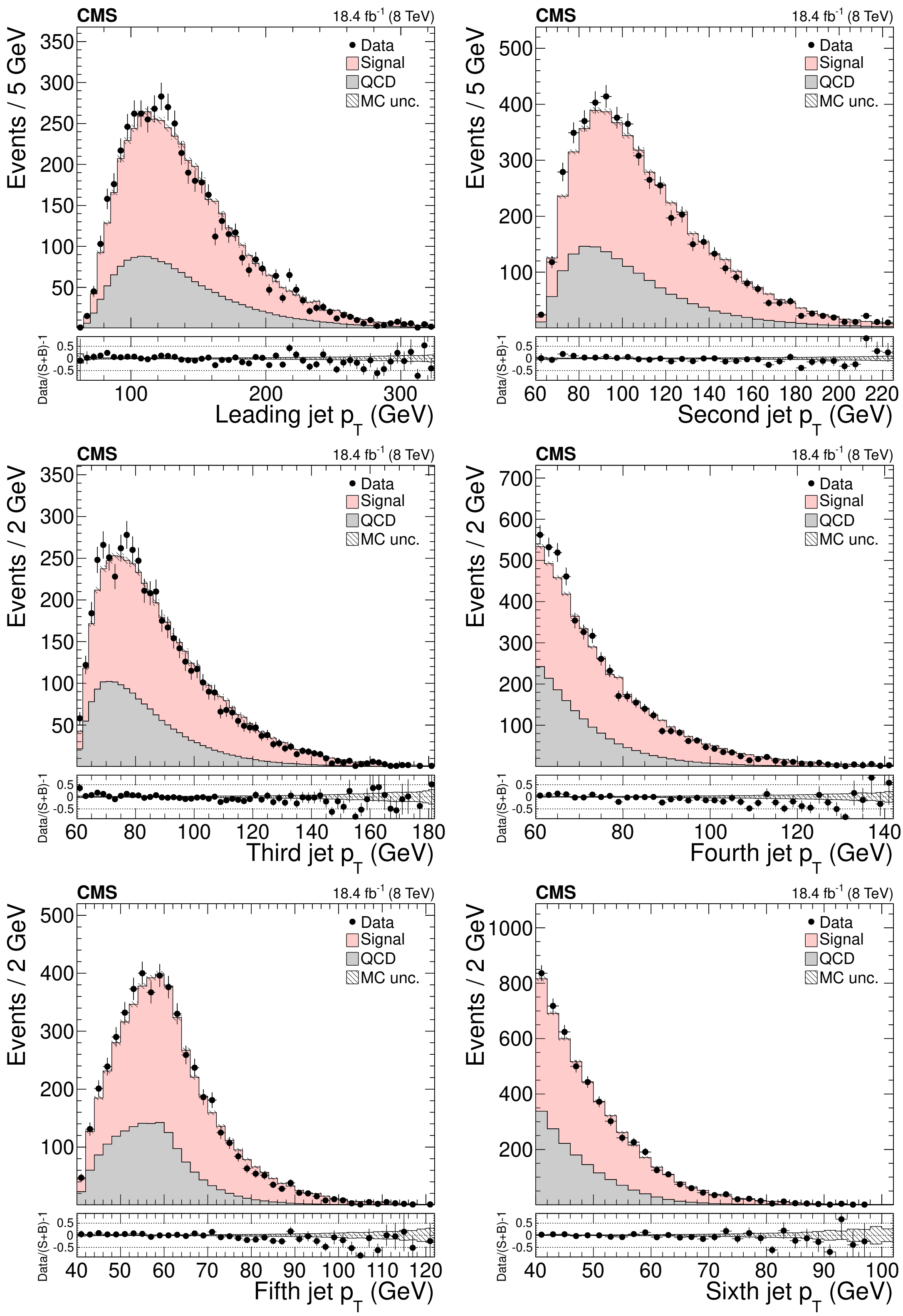

Figure 3: Distribution of the p_T of the six leading jets. The normalizations of the $t\bar{t}$ signal and the QCD multijet background are taken from the template fit to the data. The bottom panels show the fractional difference between the data and the sum of signal and background predictions, with the shaded band representing the MC statistical uncertainty.

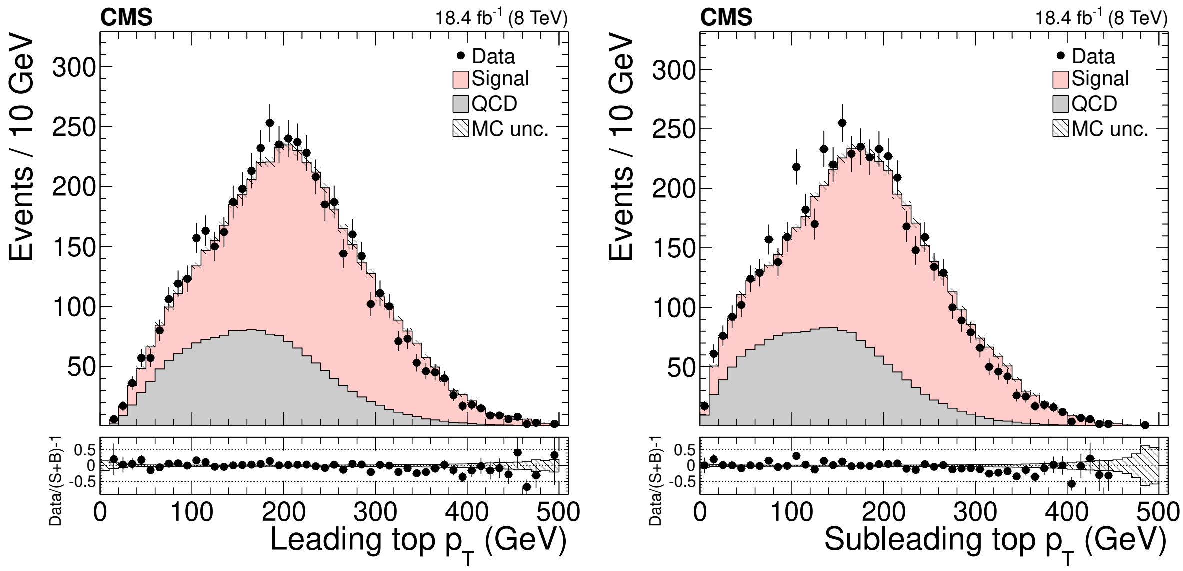

Figure 4: Distribution of the leading (left) and subleading (right) reconstructed top quark p_{T}. The normalizations of the $\mathrm{t\bar{t}}$ signal and the QCD multijet background are taken from the template fit to the data. The bottom panels show the fractional difference between the data and the sum of signal and background predictions, with the shaded band representing the MC statistical uncertainty.

GRAPH, Q is defined by $Q^2 = m_{\mathrm{t}}^2 + \Sigma p_{\mathrm{T}}^2$, where the sum is over all additional final state partons in the matrix element calculations. The effect on the measured cross section is moderate and asymmetric (-0.5, $+3.8\%$).

- **Parton distribution functions:** following the PDF4LHC prescription [50, 51], the uncertainty on the cross section is estimated to be 1.5%, taking the largest deviation on the signal acceptance from all the considered PDF eigenvectors.
- **Non-perturbative QCD:** the impact of non-perturbative QCD effects is estimated by studying various tunes of the PYTHIA shower model that predict different underlying event (UE) activity and strength of the color reconnection (CR), namely, the Perugia 2011, Perugia 2011 mpiHi, and Perugia 2011 Tevatron tunes, described in Ref. [52], were used. The effect on the measured cross section is moderate: 4.4% for the UE and 1.4% for the CR.
- **Hadronization model:** the effect of the hadronization model on the signal efficiency is estimated by comparing the predictions from the MC@NLO +HERWIG and POWHEG +PYTHIA simulations, and it amounts to 2%.

7 Results

7.1 Inclusive cross section

The signal yield ($N_{\mathrm{t\bar{t}}}$), extracted as described in Section 5, is used to compute the inclusive $\mathrm{t\bar{t}}$ production cross section, according to the formula

$$\sigma_{\mathrm{t\bar{t}}} = \frac{N_{\mathrm{t\bar{t}}}}{(\mathcal{A}\epsilon)\ \mathcal{L}}, \tag{1}$$

where $(\mathcal{A}\,\epsilon)$ is the simulated signal acceptance times efficiency in the measurement phase space ($\approx 7 \times 10^{-4}$) corrected event-by-event with the trigger and b tagging efficiency scale factors

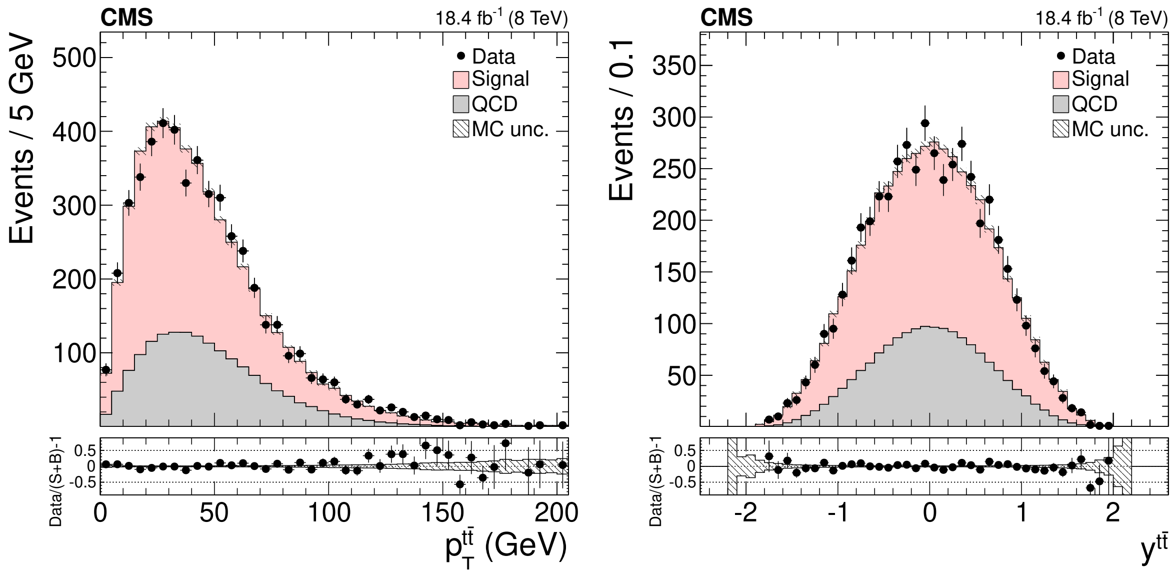

Figure 5: Distribution of the p_{T} (left) and the rapidity (right) of the reconstructed top quark pair. The normalizations of the $\mathrm{t\bar{t}}$ signal and the QCD multijet background are taken from the template fit to the data. The bottom panels show the fractional difference between the data and the sum of signal and background predictions, with the shaded band representing the MC statistical uncertainty.

Table 1: Fractional uncertainties in the inclusive $\mathrm{t\bar{t}}$ production cross section.

Source	
Background modeling	$\pm 4.9\%$
JES	$-7.0, +6.8\%$
JER	$\pm 3.5\%$
b tagging	$\pm 7.3\%$
Trigger efficiency	$-2.2, +2.0\%$
Underlying event	$\pm 4.4\%$
Matching partons to showers	$-4.2, +2.4\%$
Factorization and renormalization scales	$-0.5, +3.8\%$
Color reconnection	$\pm 1.4\%$
Parton distribution function	$\pm 1.5\%$
Hadronization	$\pm 2.0\%$
Total systematic uncertainty	$\pm 13.7\%$
Statistical uncertainty	$\pm 2.3\%$
Integrated luminosity	$\pm 2.6\%$

and $\mathcal{L}$ is the integrated luminosity. The fitted signal amounts to 3416 ± 79 events. Taking into account the systematic uncertainties discussed in Section 6, the measured cross section is

$$\sigma_{\mathrm{t\bar{t}}} = 275.6 \pm 6.1\,(\mathrm{stat}) \pm 37.8\,(\mathrm{syst}) \pm 7.2\,(\mathrm{lumi})\,\mathrm{pb}. \tag{2}$$

The precision of the measured inclusive cross section is dominated by the systematic uncertainties, and in particular by those related to JES and b tagging.

In order to parametrize the dependence of the result on the top quark mass assumption, the measurement was repeated using signal simulated samples with different generated top quark masses (167.5 and 175.5 GeV). The choice of the generated mass affects both the extracted signal yield and the signal efficiency. The quadratic interpolation of the measurements with the three different top quark masses is

$$\frac{\sigma_{\mathrm{t\bar{t}}}(m_{\mathrm{t}})}{\sigma_{\mathrm{t\bar{t}}}(m_{\mathrm{t}} = 172.5)} = 1.0 - 2.4 \times 10^{-2}\,(m_{\mathrm{t}} - 172.5) + 8.3 \times 10^{-4}\,(m_{\mathrm{t}} - 172.5)^2 . \quad (3)$$

7.2 Differential cross sections

The size of the signal sample allows the differential measurement of the $\mathrm{t\bar{t}}$ production cross section to be performed as a function of various observables. In order to confront the theoretical predictions, the differential cross sections are reported normalized to the inclusive cross section, resulting in a significant cancellation of systematic uncertainties.

The process of measuring the differential cross sections is identical to the inclusive case: in each bin of the observable used to divide the phase space, the signal is extracted from a template fit to the reconstructed top quark mass. Besides the physics interest, the choice of the observables used is mainly motivated by their correlation to $m_{\mathrm{t}}^{\mathrm{rec}}$, and the ability to extract smooth signal and background templates. The variables chosen are the p_{T} of the two reconstructed top quarks. Figure 6 shows the fitted $m_{\mathrm{t}}^{\mathrm{rec}}$ distributions in bins of the p_{T} of the leading top quark.

The differential measurements are first reported for the visible fiducial volume, as a function of the reconstructed top p_{T} (detector level), and then extrapolated to the parton and particle levels. The detector-level result is shown in Fig. 7 and is free of most of the systematic uncertainties affecting the inclusive measurement. The corresponding numerical values are reported in Table 2.

The parton-level results shown in Fig. 8 are obtained from the detector-level measurement, after correcting for bin migration effects and extrapolating to the full phase space using a bin-by-bin acceptance correction. The unfolding of the bin-migration effect is performed with the D'Agostini method [53], implemented in the RooUnfold package [54], using the migration matrix derived from the simulation. The uncertainty due to the modeling of the migration matrix and the phase-space extrapolation is estimated by repeating the unfolding and acceptance-correction procedures by varying the systematic sources described in Section 6. The numerical values of the normalized differential cross sections at parton level are reported in Table 3. It should be noted that there is a large extrapolation factor involved from the detector-level jets ($\approx 7 \times 10^{-4}$ of the signal) to the full parton level, which results in large theoretical uncertainties.

In addition to the parton level, results are reported at particle level, in Fig. 9, in a phase space similar to the detector level by construction. This is defined as follows: first, particle jets are built in simulation from all stable particles (including neutrinos) with the same jet clustering algorithm as the detector jets. Then, starting from the six leading jets, the jets associated with B hadrons via matching in η-ϕ ($\Delta R < 0.25$) are identified as the b jet candidates. Events are further selected if $p_{\mathrm{T}}^{\text{4th jet}} > 60\,\mathrm{GeV}$ and $p_{\mathrm{T}}^{\text{6th jet}} > 40\,\mathrm{GeV}$ and if there are at least two b jets with $\Delta R_{\mathrm{bb}} > 2.0$. For the selected events, a "pseudo top quark" is reconstructed from one b jet and the two closest non-b-tagged jets. The particle-level results are obtained in a similar way to the parton level, via unfolding and acceptance correction. The numerical values of the normalized differential cross sections at particle level are reported in Table 4.

The comparison of the measured and predicted differential top quark p_{T} shapes reveals that the models predict a harder spectrum, both in the leading and in the subleading top quark p_{T}, in the phase space of the measurement. This effect is also reflected on the jet p_{T} distributions shown in Fig. 3. The POWHEG +HERWIG prediction is the closest to the data, but still shows a significant discrepancy. The parton-level results are accompanied by sizeable systematic uncertainties, dominated by the theoretical uncertainties due to the extrapolation to the full phase space. In contrast, the particle-level phase space is much closer to the visible one, and as a result the extrapolation uncertainties are smaller.

Table 2: Normalized differential $\mathrm{t\bar{t}}$ cross section as a function of the p_{T} of the leading ($p_{\mathrm{T}}^{(1)}$) and subleading ($p_{\mathrm{T}}^{(2)}$) top quarks or antiquarks. The results are presented at detector level in the visible phase space.

p_{T} bin range (GeV)	$\frac{1}{\sigma}\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{(1)}\,(\mathrm{GeV}^{-1})$	stat (%)	syst (%)
[0, 150]	1.72×10^{-3}	±6.7	±3.7
[150, 225]	4.51×10^{-3}	±3.7	±2.0
[225, 300]	3.41×10^{-3}	±3.9	±1.8
[300, 375]	1.60×10^{-3}	±5.3	±1.6
[375, 500]	2.33×10^{-4}	±10.4	±1.7

p_{T} bin range (GeV)	$\frac{1}{\sigma}\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{(2)}\,(\mathrm{GeV}^{-1})$	stat (%)	syst (%)
[0, 150]	2.59×10^{-3}	±3.9	±3.3
[150, 225]	4.39×10^{-3}	±3.4	±1.9
[225, 300]	2.71×10^{-3}	±4.1	±1.9
[300, 375]	8.64×10^{-4}	±7.0	±1.8
[375, 500]	1.01×10^{-4}	±15.2	±1.7

8 Summary

A measurement of the $\mathrm{t\bar{t}}$ production cross section has been performed in the all-jets final state, using pp collision data at $\sqrt{s} = 8\,\mathrm{TeV}$ corresponding to an integrated luminosity of $18.4\,\mathrm{fb}^{-1}$. The measured inclusive cross section is $275.6 \pm 6.1\,(\mathrm{stat}) \pm 37.8\,(\mathrm{syst}) \pm 7.2\,(\mathrm{lumi})\,\mathrm{pb}$ for a top quark mass of 172.5 GeV, in agreement with the standard model prediction of $252.9^{+6.4}_{-8.6}\,(\mathrm{scale}) \pm 11.7\,(\mathrm{PDF} + \alpha_S)\,\mathrm{pb}$ as calculated with the TOP++ (v. 2.0) program [55] at next-to-next-to-leading order in perturbative QCD, including soft-gluon resummation at next-to-next-to-leading-log order [56], and assuming a top-quark mass $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$. Also reported are the fiducial normalized differential cross sections as a function of the leading and subleading top quark p_{T}. Compared to QCD predictions, the measurement shows a significantly softer top quark p_{T} spectrum. The differential cross sections are also extrapolated to the full partonic phase space, as well as to particle level, and can be used to tune Monte Carlo models.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus);

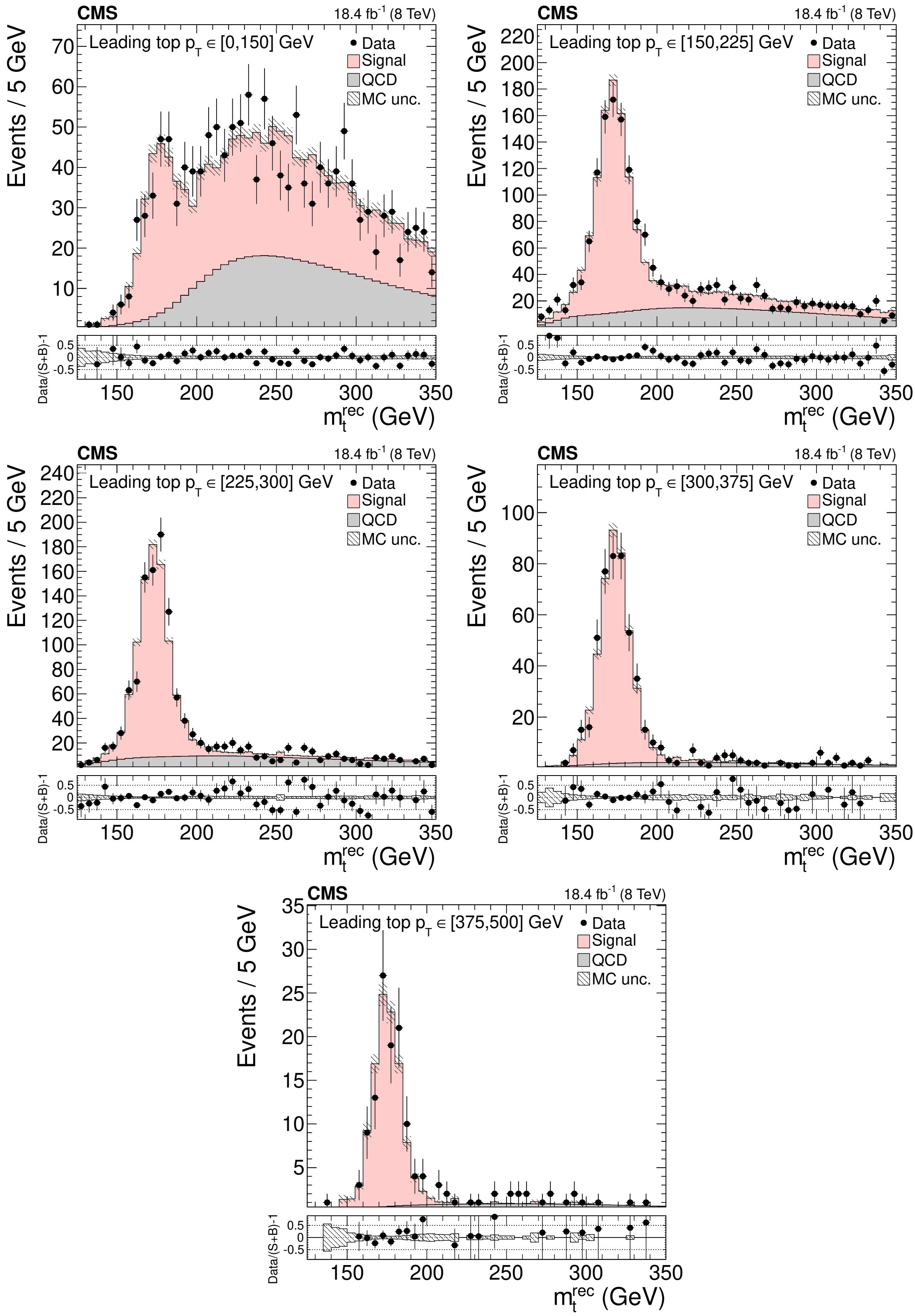

Figure 6: Distribution of the reconstructed top quark mass after the kinematic fit in bins of the leading reconstructed top quark p_{T}. The normalizations of the $\mathrm{t\bar{t}}$ signal and the QCD multijet background are taken from the template fit to the data. The bottom panels show the fractional difference between the data and the sum of signal and background predictions, with the shaded band representing the MC statistical uncertainty.

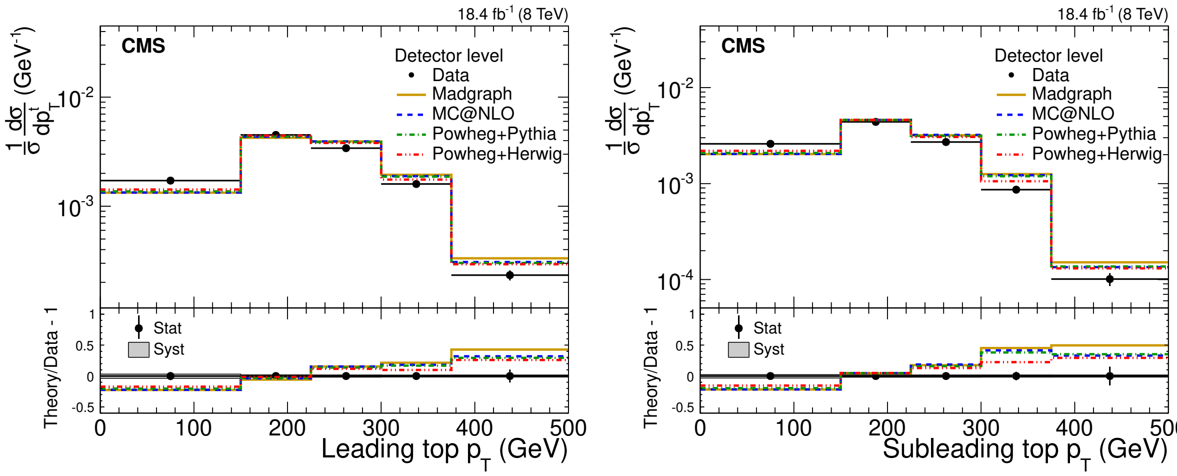

Figure 7: Normalized fiducial differential cross section of the $t\bar{t}$ production as a function of the leading (left) and subleading (right) reconstructed top quark p_T (detector level). The bottom panels show the fractional difference between various MC predictions and the data. Statistical uncertainties are shown with error bars, and systematic uncertainties with the shaded band.

Table 3: Normalized differential $t\bar{t}$ cross section as a function of the p_T of the leading ($p_T^{(1)}$) and subleading ($p_T^{(2)}$) top quarks or antiquarks. The results are presented at parton level in the full phase space.

p_T bin range (GeV)	$\frac{1}{\sigma}d\sigma/dp_T^{(1)}$ (GeV^{-1})	stat (%)	exp. syst (%)	theo. syst (%)
[0, 150]	6.72×10^{-3}	±10.8	−3.7, +4.1	−9.7, +14.8
[150, 225]	3.27×10^{-3}	±4.3	−2.0, +1.8	−9.0, +2.5
[225, 300]	8.73×10^{-4}	±5.0	−0.8, +1.2	−9.3, +4.9
[300, 375]	2.70×10^{-4}	±7.1	−2.3, +2.7	−7.5, +9.9
[375, 500]	5.88×10^{-5}	±15.2	−3.3, +1.9	−29.4, +9.0

p_T bin range (GeV)	$\frac{1}{\sigma}d\sigma/dp_T^{(2)}$ (GeV^{-1})	stat (%)	exp. syst (%)	theo. syst (%)
[0, 150]	7.59×10^{-3}	±6.2	−2.5, +2.7	−7.6, +8.1
[150, 225]	1.73×10^{-3}	±4.4	−1.3, +0.7	−10.5, +4.7
[225, 300]	4.12×10^{-4}	±5.6	−1.8, +2.2	−15.7, +6.2
[300, 375]	9.11×10^{-5}	±9.7	−1.9, +3.3	−18.1, +7.0
[375, 500]	2.30×10^{-5}	±21.4	−5.6, +2.0	−15.0, +4.7

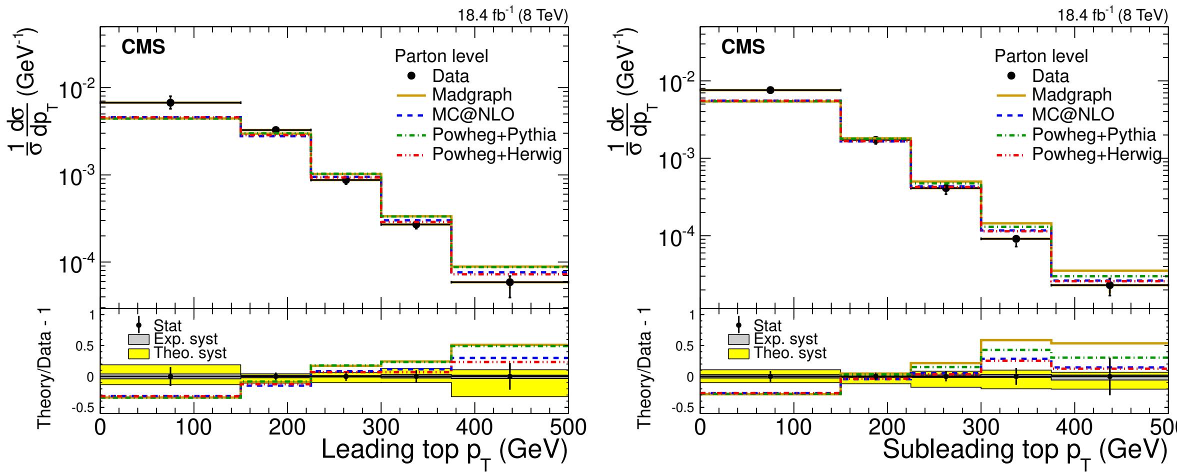

Figure 8: Normalized differential cross section of the $t\bar{t}$ production at parton level as a function of the leading (left) and subleading (right) top quark p_{T}. The bottom panels show the fractional difference between various MC predictions and the data. Statistical uncertainties are shown with error bars, while theoretical (theo.) and experimental (exp.) systematic uncertainties with the shaded bands.

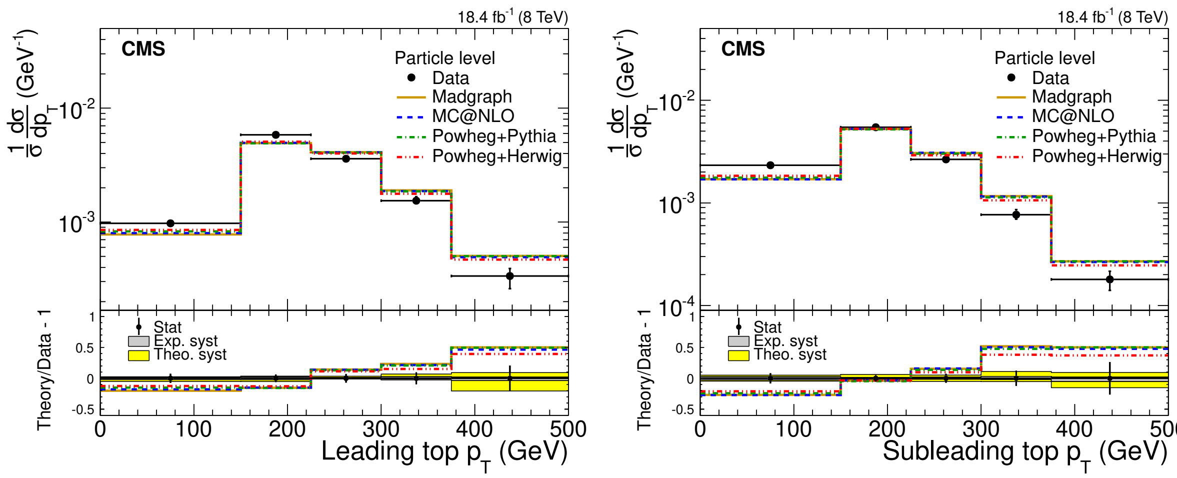

Figure 9: Normalized differential cross section of the $t\bar{t}$ production at particle level as a function of the leading (left) and subleading (right) top quark p_{T}. The bottom panels show the fractional difference between various MC predictions and the data. Statistical uncertainties are shown with error bars, while theoretical (theo.) and experimental (exp.) systematic uncertainties with the shaded bands.

MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Re-

Table 4: Normalized differential $\mathrm{t\bar{t}}$ cross section as a function of the p_T of the leading ($p_\mathrm{T}^{(1)}$) and subleading ($p_\mathrm{T}^{(2)}$) top quarks or antiquarks. The results are presented at particle level.

p_T bin range (GeV)	$\frac{1}{\sigma}\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}^{(1)}\,(\mathrm{GeV}^{-1})$	stat (%)	exp. syst (%)	theo. syst (%)
$[0, 150]$	9.75×10^{-4}	± 5.2	$-2.2, +1.5$	$-2.9, +1.0$
$[150, 225]$	5.83×10^{-3}	± 4.4	$-2.3, +2.3$	$-3.0, +1.2$
$[225, 300]$	3.60×10^{-3}	± 5.0	$-0.7, +1.3$	$-0.0, +3.1$
$[300, 375]$	1.54×10^{-3}	± 6.8	$-2.2, +2.5$	$-0.4, +4.3$
$[375, 500]$	3.36×10^{-4}	± 14.6	$-3.6, +1.8$	$-16.9, +7.4$

p_T bin range (GeV)	$\frac{1}{\sigma}\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}^{(2)}\,(\mathrm{GeV}^{-1})$	stat (%)	exp. syst (%)	theo. syst (%)
$[0, 150]$	2.33×10^{-3}	± 5.8	$-2.5, +2.5$	$-3.3, +3.6$
$[150, 225]$	5.46×10^{-3}	± 3.8	$-1.5, +1.2$	$-3.4, +5.1$
$[225, 300]$	2.66×10^{-3}	± 5.1	$-1.4, +1.8$	$-3.9, +3.9$
$[300, 375]$	7.67×10^{-4}	± 8.6	$-1.7, +3.0$	$-4.0, +8.5$
$[375, 500]$	1.80×10^{-4}	± 18.6	$-5.0, +1.9$	$-11.4, +7.8$

search Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the OPUS programme of the National Science Center (Poland); the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); and the Welch Foundation, contract C-1845.

References

[1] ATLAS Collaboration, "Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **71** (2011) 1577, doi:10.1140/epjc/s10052-011-1577-6, arXiv:1012.1792.

[2] ATLAS Collaboration, "Measurement of the top quark pair production cross section in pp collisions at $\sqrt{s} = 7$ TeV in dilepton final states with ATLAS", *Phys. Lett. B* **707** (2012) 459, doi:10.1016/j.physletb.2011.12.055, arXiv:1108.3699.

[3] ATLAS Collaboration, "Measurement of the top quark pair production cross-section with ATLAS in the single lepton channel", *Phys. Lett. B* **711** (2012) 244, doi:10.1016/j.physletb.2012.03.083, arXiv:1201.1889.

[4] ATLAS Collaboration, "Measurement of the cross section for top-quark pair production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector using final states with two high-pt leptons", *JHEP* **05** (2012) 059, doi:10.1007/JHEP05(2012)059, arXiv:1202.4892.

[5] ATLAS Collaboration, "Measurement of the top quark pair cross section with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV using final states with an electron or a muon and a hadronically decaying τ lepton", *Phys. Lett. B* **717** (2012) 89, doi:10.1016/j.physletb.2012.09.032, arXiv:1205.2067.

[6] ATLAS Collaboration, "Measurement of the ttbar production cross section in the tau+jets channel using the ATLAS detector", *Eur. Phys. J. C* **73** (2013) 2328, doi:10.1140/epjc/s10052-013-2328-7, arXiv:1211.7205.

[7] ATLAS Collaboration, "Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b -tagged jets in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector", *Eur. Phys. J. C* **74** (2014) 3109, doi:10.1140/epjc/s10052-014-3109-7, arXiv:1406.5375.

[8] ATLAS Collaboration, "Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector", *Phys. Rev. D* **90** (2014) 072004, doi:10.1103/PhysRevD.90.072004, arXiv:1407.0371.

[9] ATLAS Collaboration, "Differential top-antitop cross-section measurements as a function of observables constructed from final-state particles using pp collisions at $\sqrt{s} = 7$ TeV in the ATLAS detector", *JHEP* **06** (2015) 100, doi:10.1007/JHEP06(2015)100, arXiv:1502.05923.

[10] ATLAS Collaboration, "Measurement of the top pair production cross section in 8 TeV proton-proton collisions using kinematic information in the lepton+jets final state with ATLAS", *Phys. Rev. D* **91** (2015) 112013, doi:10.1103/PhysRevD.91.112013, arXiv:1504.04251.

[11] ATLAS Collaboration, "Measurement of the top quark branching ratios into channels with leptons and quarks with the ATLAS detector", *Phys. Rev. D* **92** (2015) 072005, doi:10.1103/PhysRevD.92.072005, arXiv:1506.05074.

[12] CMS Collaboration, "First measurement of the cross section for top-quark pair production in proton-proton collisions at $\sqrt{s} = 7$ TeV", *Phys. Lett. B* **695** (2011) 424, doi:10.1016/j.physletb.2010.11.058, arXiv:1010.5994.

[13] CMS Collaboration, "Measurement of the $\mathrm{t\bar{t}}$ production cross section and the top quark mass in the dilepton channel in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **07** (2011) 049, doi:10.1007/JHEP07(2011)049, arXiv:1105.5661.

[14] CMS Collaboration, "Measurement of the $\mathrm{t\bar{t}}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV using the kinematic properties of events with leptons and jets", *Eur. Phys. J. C* **71** (2011) 1721, doi:10.1140/epjc/s10052-011-1721-3, arXiv:1106.0902.

[15] CMS Collaboration, "Measurement of the $t\bar{t}$ Production Cross Section in pp Collisions at 7 TeV in Lepton + Jets Events Using b-quark Jet Identification", *Phys. Rev. D* **84** (2011) 092004, doi:10.1103/PhysRevD.84.092004, arXiv:1108.3773.

[16] CMS Collaboration, "Measurement of the $\mathrm{t\bar{t}}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV in dilepton final states containing a τ", *Phys. Rev. D* **85** (2012) 112007, doi:10.1103/PhysRevD.85.112007, arXiv:1203.6810.

[17] CMS Collaboration, "Measurement of the $\mathrm{t\bar{t}}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **11** (2012) 067, doi:10.1007/JHEP11(2012)067, arXiv:1208.2671.

[18] CMS Collaboration, "Measurement of differential top-quark pair production cross sections in pp colisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **73** (2013) 2339, doi:10.1140/epjc/s10052-013-2339-4, arXiv:1211.2220.

[19] CMS Collaboration, "Measurement of the $\mathrm{t\bar{t}}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV with lepton+jets final states", *Phys. Lett. B* **720** (2013) 83, doi:10.1016/j.physletb.2013.02.021, arXiv:1212.6682.

[20] CMS Collaboration, "Measurement of the $\mathrm{t\bar{t}}$ production cross section in the tau+jets channel in pp collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **73** (2013) 2386, doi:10.1140/epjc/s10052-013-2386-x, arXiv:1301.5755.

[21] CMS Collaboration, "Measurement of the $t\bar{t}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **05** (2013) 065, doi:10.1007/JHEP05(2013)065, arXiv:1302.0508.

[22] CMS Collaboration, "Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s} = 8$ TeV", *JHEP* **02** (2014) 024, doi:10.1007/JHEP02(2014)024, arXiv:1312.7582. [Erratum: doi:10.1007/JHEP02(2014)102].

[23] CMS Collaboration, "Measurement of the $\mathrm{t\bar{t}}$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV in dilepton final states containing one τ lepton", *Phys. Lett. B* **739** (2014) 23, doi:10.1016/j.physletb.2014.10.032, arXiv:1407.6643.

[24] CMS Collaboration, "Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV", *Eur. Phys. J. C* **75** (2015) 542, doi:10.1140/epjc/s10052-015-3709-x, arXiv:1505.04480.

[25] CDF, D0 Collaboration, "Combination of measurements of the top-quark pair production cross section from the Tevatron Collider", *Phys. Rev. D* **89** (2014) 072001, doi:10.1103/PhysRevD.89.072001, arXiv:1309.7570.

[26] CDF Collaboration, "Measurement of the Top Quark Mass and $p\bar{p} \to t\bar{t}$ Cross Section in the All-Hadronic Mode with the CDFII Detector", *Phys. Rev. D* **81** (2010) 052011, doi:10.1103/PhysRevD.81.052011, arXiv:1002.0365.

[27] D0 Collaboration, "Measurement of the $t\bar{t}$ cross section using high-multiplicity jet events", *Phys. Rev. D* **82** (2010) 032002, doi:10.1103/PhysRevD.82.032002, arXiv:0911.4286.

[28] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[29] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[30] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, "Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations", *JHEP* **03** (2013) 015, doi:10.1007/JHEP03(2013)015, arXiv:1212.3460.

[31] J. Pumplin et al., "New generation of parton distributions with uncertainties from global QCD analysis", *JHEP* **07** (2002) 012, doi:10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.

[32] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 physics and manual", *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[33] M. L. Mangano, M. Moretti, F. Piccinini, and M. Treccani, "Matching matrix elements and shower evolution for top-quark production in hadronic collisions", *JHEP* **01** (2007) 013, doi:10.1088/1126-6708/2007/01/013, arXiv:hep-ex/0611129.

[34] R. Field, "Early LHC Underlying Event Data - Findings and Surprises", in *Hadron collider physics. Proceedings, 22nd Conference, HCP 2010, Toronto, Canada, August 23-27, 2010.* 2010. arXiv:1010.3558.

[35] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[36] S. Frixione and B. R. Webber, "Matching NLO QCD computations and parton shower simulations", *JHEP* **06** (2002) 29, doi:10.1088/1126-6708/2002/06/029, arXiv:hep-ph/0204244.

[37] P. Nason, "A New method for combining NLO QCD with shower Monte Carlo algorithms", *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[38] G. Corcella et al., "HERWIG 6: An event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)", *JHEP* **01** (2001) 010, doi:10.1088/1126-6708/2001/01/010, arXiv:hep-ph/0011363.

[39] ATLAS Collaboration, "ATLAS tunes of PYTHIA 6 and Pythia 8 for MC11", ATLAS PUB note ATL-PHYS-PUB-2011-009, 2011.

[40] L. Hung-Liang et al., "New parton distributions for collider physics", *Phys. Rev. D* **82** (2010) 074024, doi:10.1103/PhysRevD.82.074024, arXiv:hep-ph/1007.2241.

[41] M. Cacciari and G. P. Salam, "Dispelling the N^3 myth for the k_t jet-finder", *Phys. Lett. B* **641** (2006) 57, doi:10.1016/j.physletb.2006.08.037, arXiv:hep-ph/0512210.

[42] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_t jet clustering algorithm", *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[43] CMS Collaboration, "Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and $E_{\mathrm{T}}^{\mathrm{miss}}$", CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.

[44] CMS Collaboration, "Commissioning of the Particle-flow Event Reconstruction with the first LHC collisions recorded in the CMS detector", CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010.

[45] CMS Collaboration, "Determination of jet energy calibration and transverse momentum resolution in CMS", *J. Instrum.* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002.

[46] CMS Collaboration, "Identification of b-quark jets with the CMS experiment", *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.

[47] Particle Data Group Collaboration, "Review of Particle Physics", *Chin. Phys. C* **38** (2014) 090001, doi:10.1088/1674-1137/38/9/090001.

[48] CMS Collaboration, "Measurement of the top-quark mass in all-jets $\mathrm{t\bar{t}}$ events in pp collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **74** (2014) 2758, doi:10.1140/epjc/s10052-014-2758-x, arXiv:1307.4617.

[49] CMS Collaboration, "CMS Luminosity Based on Pixel Cluster Counting - Summer 2013 Update", CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013.

[50] S. Alekhin et al., "The PDF4LHC Working Group Interim Report", (2011). arXiv:1101.0536.

[51] M. Botje et al., "The PDF4LHC Working Group Interim Recommendations", (2011). arXiv:1101.0538.

[52] P. Z. Skands, "Tuning Monte Carlo Generators: The Perugia Tunes", *Phys. Rev. D* **82** (2010) 074018, doi:10.1103/PhysRevD.82.074018, arXiv:1005.3457.

[53] G. D'Agostini, "A multidimensional unfolding method based on Bayes' theorem", *Nucl. Instrum. Meth. A* **362** (1995) 487, doi:10.1016/0168-9002(95)00274-X.

[54] T. Adye, "Unfolding algorithms and tests using RooUnfold", in *Proceedings of the PHYSTAT 2011 Workshop, CERN, Geneva, Switzerland, January 2011, CERN-2011-006*, p. 313. 2011. arXiv:1105.1160.

[55] M. Czakon and A. Mitov, "Top++: A program for the calculation of the top-pair cross-section at hadron colliders", *Comput. Phys. Commun.* **185** (2014) 2930, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.

[56] M. Czakon, P. Fiedler, and A. Mitov, "Total Top-Quark Pair-Production Cross Section at Hadron Colliders Through $\mathcal{O}(\alpha_S^4)$", *Phys. Rev. Lett.* **110** (2013) 252004, doi:10.1103/PhysRevLett.110.252004, arXiv:1303.6254.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], V. Knünz, A. König, M. Krammer[1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady[2], B. Rahbaran, H. Rohringer, J. Schieck[1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, G. Fasanella, L. Favart, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang[3]

Ghent University, Ghent, Belgium
K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi[4], O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco[5], J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov[6], L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, M. Hamer, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[7], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[7], A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[b], A. De Souza Santos[b], S. Dogra[a], T.R. Fernandez Perez Tomei[a],

E.M. Gregores[b], P.G. Mercadante[b], C.S. Moon[a,8], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina[9], F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger[10], M. Finger Jr.[10]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[11,12], A. Awad, M. El Sawy[13,14], A. Mahrous[11], A. Radi[14,15]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[16], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[16], X. Coubez, J.-C. Fontaine[16], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin[2], K. Skovpen, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[17]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[10]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov[6]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann[2], A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras[18], A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo[19], J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel[20], H. Jung, A. Kalogeropoulos, O. Karacheban[20], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[20], R. Mankel, I. Marfin[20], I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak,

E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo[2], T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann[2], S.M. Heindl, U. Husemann, I. Katkov[6], A. Kornmayer[2], P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, I. Topsis-Giotis

University of Athens, Athens, Greece
A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece
I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath[21], F. Sikler, V. Veszpremi, G. Vesztergombi[22], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[23], J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary
M. Bartók[24], A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
P. Mal, K. Mandal, D.K. Sahoo, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U.Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[2], L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, S. Bhowmik[25], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu[26], G. Kole, S. Kumar, B. Mahakud, M. Maity[25], G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar[25], N. Sur, B. Sutar, N. Wickramage[27]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami[28], A. Fahim[29], R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh[30], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], C. Caputo[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,c], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a,2], R. Venditti[a,b], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[2], A.C. Benvenuti[a], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], CSFNSM [c], Catania, Italy
G. Cappello[a], M. Chiorboli[a,b], S. Costa[a,b], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Gonzi[a,b], V. Gori[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,b], L. Viliani[a,b]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], M. Lo Vetere[a,b], M.R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
L. Brianza, M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], B. Marzocchi[a,b,2], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della

Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], S. Di Guida[a,d,2], M. Esposito[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], G. Lanza[a], L. Lista[a], S. Meola[a,d,2], M. Merola[a], P. Paolucci[a,2], C. Sciacca[a,b], F. Thyssen

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a,2], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b,2], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Michelotto[a], F. Montecassiano[a], M. Passaseo[a], J. Pazzini[a,b], M. Pegoraro[a], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], S. Vanini[a,b], M. Zanetti, P. Zotto[a,b], A. Zucchetta[a,b,2]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
L. Alunni Solestizi[a,b], M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b,2], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a,31], P. Azzurri[a], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], M.A. Ciocci[a,31], R. Dell'Orso[a], S. Donato[a,c,2], G. Fedi, L. Foà[a,c†], A. Giassi[a], M.T. Grippo[a,31], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,b], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A. Savoy-Navarro[a,32], A.T. Serban[a], P. Spagnolo[a], P. Squillacioti[a,31], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], G. D'imperio[a,b,2], D. Del Re[a,b], M. Diemoz[a], S. Gelli[a,b], C. Jorda[a], E. Longo[a,b], F. Margaroli[a,b], P. Meridiani[a], G. Organtini[a,b], R. Paramatti[a], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], P. Traczyk[a,b,2]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c,2], S. Argiro[a,b], M. Arneodo[a,c], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], L. Finco[a,b,2], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Musich[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], U. Tamponi[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b,2], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], C. La Licata[a,b], M. Marone[a,b], A. Schizzi[a,b], A. Zanetti[a]

Kangwon National University, Chunchon, Korea
A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea
J.A. Brochero Cifuentes, H. Kim, T.J. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
S. Song

Korea University, Seoul, Korea
S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
H.D. Yoo

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali[33], F. Mohamad Idris[34], W.A.T. Wan Abdullah, M.N. Yusli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[35], A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, A. Byszuk[36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho,

M. Gallinaro, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev[37], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[38], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[39], I. Dremin[39], M. Kirakosyan, A. Leonidov[39], G. Mesyats, S.V. Rusakov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[40], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, N. Korneeva, I. Lokhtin, I. Myagkov, S. Obraztsov, M. Perfilov, V. Savrin

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[41], J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli[42], L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi[43], M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas[44], J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres[22], N. Wardle, H.K. Wöhri, A. Zagozdzinska[36], W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Quittnat, M. Rossini, A. Starodumov[45], M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[46], L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, Y. Yang

National Central University, Chung-Li, Taiwan
M. Cardaci, K.H. Chen, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
Arun Kumar, R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[47], Z.S. Demiroglu, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis,

G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal[48], A. Kayis Topaksu, G. Onengut[49], K. Ozdemir[50], A. Polatoz, D. Sunar Cerci[51], M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, B. Bilin, S. Bilmis, B. Isildak[52], G. Karapinar[53], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E.A. Albayrak[54], E. Gülmez, M. Kaya[55], O. Kaya[56], T. Yetkin[57]

Istanbul Technical University, Istanbul, Turkey
K. Cankocak, S. Sen[58], F.I. Vardarlı

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold[59], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[60], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Kenzie, R. Lane, R. Lucas[59], L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko[45], J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta[61], T. Virdee, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

Brown University, Providence, USA
J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, N. Dhingra, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, T. Sinthuprasith, R. Syarif

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA
R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[62], C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, W. To, C. West, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan[†], S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, H.A. Weber, A. Whitbeck, F. Yang

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic[63], G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi[64], M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

The University of Iowa, Iowa City, USA
B. Bilki[65], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[66], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[54], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
I. Anderson, B.A. Barnett, B. Blumenfeld, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, A. Sady, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, C. Bruner, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, S. Sanders, R. Stringer, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. Mcginn, C. Mironov, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA
B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northwestern University, Evanston, USA
K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[37], T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA
S. Malik

Purdue University, West Lafayette, USA
V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University Calumet, Hammond, USA
N. Parashar, J. Stupak

Rice University, Houston, USA
A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, P. Tan, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA
O. Bouhali[67], A. Castaneda Hernandez[67], M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Kamon[68], V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer[2]

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin, Madison, USA
D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Helwan University, Cairo, Egypt

12: Now at Zewail City of Science and Technology, Zewail, Egypt
13: Also at Beni-Suef University, Bani Sweif, Egypt
14: Now at British University in Egypt, Cairo, Egypt
15: Now at Ain Shams University, Cairo, Egypt
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at Tbilisi State University, Tbilisi, Georgia
18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
19: Also at University of Hamburg, Hamburg, Germany
20: Also at Brandenburg University of Technology, Cottbus, Germany
21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
22: Also at Eötvös Loránd University, Budapest, Hungary
23: Also at University of Debrecen, Debrecen, Hungary
24: Also at Wigner Research Centre for Physics, Budapest, Hungary
25: Also at University of Visva-Bharati, Santiniketan, India
26: Now at King Abdulaziz University, Jeddah, Saudi Arabia
27: Also at University of Ruhuna, Matara, Sri Lanka
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at Purdue University, West Lafayette, USA
33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at National Technical University of Athens, Athens, Greece
43: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
44: Also at University of Athens, Athens, Greece
45: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
46: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
47: Also at Gaziosmanpasa University, Tokat, Turkey
48: Also at Mersin University, Mersin, Turkey
49: Also at Cag University, Mersin, Turkey
50: Also at Piri Reis University, Istanbul, Turkey
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Ozyegin University, Istanbul, Turkey
53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
55: Also at Marmara University, Istanbul, Turkey
56: Also at Kafkas University, Kars, Turkey
57: Also at Yildiz Technical University, Istanbul, Turkey
58: Also at Hacettepe University, Ankara, Turkey

59: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
60: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
61: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
62: Also at Utah Valley University, Orem, USA
63: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
64: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
65: Also at Argonne National Laboratory, Argonne, USA
66: Also at Erzincan University, Erzincan, Turkey
67: Also at Texas A&M University at Qatar, Doha, Qatar
68: Also at Kyungpook National University, Daegu, Korea